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Assessment and performance evaluation of photon optimizer (PO) vs. dose volume optimizer (DVO) for IMRT and progressive resolution optimizer (PRO) for RapidArc planning using a virtual phantom

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Original Article

Abstract

Purpose: The purpose of the study was to present the quantitative and qualitative evaluation of newly incorporated photon optimizer (PO) versus previously was used independent dose volume optimizer (DVO) for intensity modulated radiation therapy (IMRT) and progressive resolution optimizer (PRO) for Rapid-arc/ volumetric modulated arc therapy (VMAT) in version 13.5 of Eclipse treatment planning system (ETPS). **Methods:** We accomplished this study with the help of cylindrical virtual phantom created in the ETPS. Six individual phantoms study sets (PSS) were generated and different material density value was assigned in order to evaluate the behavior optimizers in the presence of tissue heterogeneity. Several independent plans were generated for IMRT and Rapid-arc by changing optimizer module PO, DVO, and PRO for 6 MV, 15 MV flattened beam and 6 MV-flattening filter free (FFF) beam. **Results:** The self-governing evaluations of PO versus DVO for IMRT plan and PO versus PRO for Rapid-arc/VMAT plans were performed. We estimated and compared various distinct parameters such as maximum dose, minimum dose, mean dose, conformity index (CI), quality index (QI), homogeneity index (HI), integral plan monitor unit (MU) and dose volume histogram (DVH). The percentages of the average variation over all PSS and beam energy between PO versus DVO optimized plan quality parameters such as planning target volume (PTV) maximum, minimum, mean doses, CI, QI and HI were 0.23%, 1.67%, 0.09%, 20.4%, 0.77% and 0.52% , respectively, whereas for PO versus PRO were 1.18%, 3.38%, 0.19%, 8.11%, 2.78%, and 1.28%, respectively. **Conclusion:** The results presented in this study showed that PO generates plans with better quality in shorter time compared to DVO and PRO for both IMRT and Rapid-arc/VMAT, respectively.

Keywords: Optimization, Dose Volume Optimizer, Progressive Resolution Optimizer, Photon Optimizer, IMRT, Rapid-arc

1. Introduction

Efficient delivery of intensity modulated radiation therapy (IMRT) requires the concept of "Physical Optimization".[1-2] Over the due course of time, numerous optimization algorithms[3] have been developed for IMRT planning optimization. Distinct objective functions were used to attain IMRT planning goal. Since, different mathematical properties of the objective function forbid to use single optimization algorithm. Thereby, separate optimization algorithms used as per the objective function to achieve desired goal. The current practical approach of all optimizations based on an iterative optimization scheme. Previously, based on deterministic and conjugate gradient approachs[4], several algorithms such as steepest decent, Newton Method, Stochastic Method, Simulated Annealing, Boltzman Annealing and Fast Simulated Annealing were developed to control

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various parameters. Over the period direct aperture optimization (DAO)[5] was developed for simultaneous optimization of beam weight and shape of the aperture, in order to add more degree of freedom to aperture based planning approach. Similarly, several optimizers such as direct machine parameter optimizer (DMPO)[6], plan geometry optimizer (PGO), multi resolution dose calculation (MRDC), dose volume optimizer (DVO), progressive resolution optimizer (PRO) and photon optimizer (PO) were developed for various objectives in IMRT and Rapid-arc.

Recently, Varian Medical System has incorporated PO as a new dose calculation optimizer for both static gantry IMRT optimization as well as Rapid-arc/volumetric modulated arc therapy (VMAT)[7] optimization in Eclipse treatment planning system (ETPS) version_13.5. In the older versions (lower than 13.5), ETPS is using separate optimizer DVO for IMRT whereas, PRO for Rapid-arc/ VMAT optimization. PO is supporting all features currently supported by the DVO and PRO except for DVO "field weight optimization" and "minimize dose" optimization parameter. A new feature with PO is convenient for both of static IMRT as well as Rapid-arc provides an approximation of dose distribution shown in the 2D view during optimization. Optimization objectives for generalized equivalent uniform dose (gEUD) are available for IMRT and VMAT plans. Automatic normal tissue objective (NTO), mean dose objectives and second source inhomogeneity correction are now supported for static gantry IMRT optimization. PO also supports for Siemens Modulated (mARC) optimization for machine equipped with 160 MLC, VMAT for Elekta Synergy, Agility™ and VersaHD. As the PO is included as a new calculation model, PO supports same beam configuration data as of DVO or PRO. This study has been mainly focused on an extensive comparison of recently incorporated PO optimizer versus previously being used DVO and PRO for IMRT and Rapid-arc/VMAT optimization respectively.

2. Methods and Materials

We created a volume of 21.195 × 10^3 ($\prod r^3 h$, h = 30 cm, r = 30 cm) cylindrical virtual phantom in Eclipse contouring workstation by assigning the material density of 1.0 gm/cm^3 corresponding to HU = 0 values of water. Six distinct phantom study sets (PSS) were created consisting planning target volume (PTV = 344.0 cm^3) encompassing organ at risk (OAR = 40.0 cm^3) of the similar shape and volume over all PSS. Further different structures were created around PTV in phantom by assigning various densities in order to evaluate the effect of inhomogeneity and to reproduce human media on homogeneous phantom in each PSS. The elliptical shape of a PTV encompassing circular shape of OAR was then drawn into the center of the phantom. Illustration of each of PSS given as follows. The PSS 1st were created only with PTV encompassing the OAR on homogeneous phantom. The PSS 2nd consisting of bone density ρ_2 = 1.5574 gm/cm^3 corresponds to HU = 900 and air cavity with HU = -1000 inside the PTV. PSS 3rd contained number of bony structure are less in number of density ρ_3 = 1.4373 gm/cm^3 corresponds to HU = 700, whereas air cavity structure with HU = -1000 are more in number outside the PTV. PSS 4th were created by including more number of bony structure of density ρ_4 = 1.5273 gm/cm^3 correspond HU = 850 whereas less air cavity structure around the PTV. PSS 5th and PSS 6th were created with both PTV and OAR entirely covered with an air cavity of HU = -1000 and bone density of ρ_6 = 1.6146 gm/cm^3 corresponds to HU = 1000, respectively. Transverse views of each of the study set is shown in Figure 1.

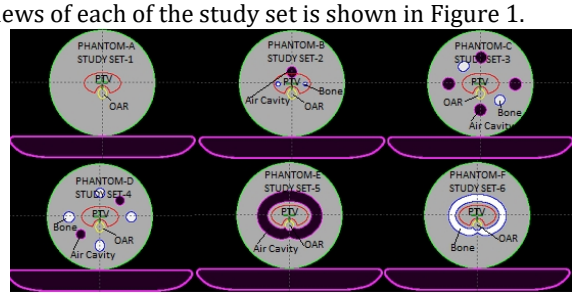

Figure 1: Different cylindrical phantom study sets (PSS). Phantom study sets 1- 6 embedded with different material density such as air, bone to represent the heterogeneous phantom.

This study was accomplished for both IMRT and Rapid-arc/VMAT technique by creating individual plan for independent PO versus DVO and PO versus PRO for IMRT and Rapid-arc/VMAT, respectively, in ETPS (Version 13.5, Varian Medical System). In order to perform comparative evaluation of IMRT and Rapid-arc/ VMAT plans with their different optimizer, we generated plan for 50 Gy/25#, 2Gy dose per fraction with 6 MV flattened, 6 MV flattening filter free (FFF) lower energy and 15 MV higher energy beam. We used analytical anisotropic algorithm (AAA) to carry out final dose calculation. All the plan specific parameter such as energy, dose prescription, gantry angle in IMRT plan, Arc-geometry in Rapid-arc/VMAT plan, penumbra margin and optimization parameter such as upper dose objective; lower dose objective, mean dose objective, normal tissue objective (NTO) and priority values were kept similar while optimizing the plan with PO versus DVO and PRO for IMRT and Rapid-arc/VMAT respectively. According to Radiation Oncology Therapy Group (RTOG) protocol, minimum plan passing criteria for target volume is that 95% of target volume should receive the 95% prescription dose and an OAR should not exceed a maximum dose of 45 Gy. Initially, all objective parameters were chosen in a way , to achieve the plan-passing criteria with PO for both IMRT and Rapid-arc/VMAT plan. Once we achieved the desired goal, then without changing any of these parameters, other plans were generated by changing the optimizer module DVO for IMRT and PRO for Rapid-arc/VMAT respectively. Entire set of 72 plans were generated to accomplish the study. Individual 36 plans for each of

IMRT plan were optimized with PO versus DVO and Rapid-arc /VMAT plan were optimized with PO versus PRO.

2.1. Optimization algorithm

An optimization algorithm determines the optimal field shape and intensity by iteratively conforming dose distribution to the desired objectives until an optimum solution is reached. The algorithm optimizes a plan based on dose-volume objectives. Optimization algorithm uses an objective function to optimize plan and to evaluate its quality. The objective function is the sum of the dose-volume and other user-defined objectives. Each optimization objective has its own four parameters such as an optimization priority (p), $dose_{goal}$ Upper (Maximum) limit, Lower (Minimum) limit and mean dose as a function of dose-volume conjunction criteria. A structure with (n) points (i) and (m) optimization objectives obtains a total cost value as[8]:

$$\sum_{j=1}^{m}\sum_{i=n}^{n} \text{objective}_{\text{weight, j}} * (\text{dose}_i - \text{dose}_{\text{goal, j}})^2 / n$$

where, $dose_i$ = Dose at Point i
$dose_{goal}$ = Prescribe dose or Upper limit

The objective weighting (W= $Objective_{weight}$) is derived from the heuristic power law formula. The cost functions for an objective j are only taken into account for the range of voxels that violate the assigned dose volume criteria. Similarly, multi-resolution dose calculation algorithm (MRDC) enables fast dose estimation inside the DVO, PRO and PO. The high speed of the MRDC algorithm allows optimization algorithms to perform full dose computation during each iteration. MRDC dose is based upon a convolution superposition principle, and it uses 3D convolution scatter computation.[9] Optimizer PO and PRO both taken into account for an air cavity correction, but DVO does not correct dose for air cavity.

2.2. Dose volume optimizer (DVO_13.5.35)

DVO algorithm is used in Eclipse IMRT to determine optimal field shape and intensity.[10] In each field; DVO lays the fluence to target projection with 5 mm margin. Then the created fluence object is expanded symmetrically to field isocenter by adding the fluence pixel to zero values. Maximum size of the fluence objects is 40×40 cm. The dose optimization algorithm performs the optimization as a minimization problem using simple gradient optimization. Initially, all the fluences are zero and alternatively; the fluence from a previous optimization is used as the initial guess. The optimization modifies these fluences for each iteration and calculates the dose from the fluence after each modification. Once the doses at the points of the clouds representing the patient volumes are evaluates; the objectives at the points and the derivatives of the point objectives are calculated. The cost functions are evaluated at each point in each structure. The derivatives of the cost at each point are back-projected to the fluences, forming the gradient. Optimization uses the gradient search method. The gradient search is divided into two phases; gradient evaluation and line search method. Gradient evaluation generates the gradient direction and gradient length. Whereas; line search evaluates the objectives on a line segment along the gradient and finds the minimum along the line segment.

The DVO algorithm can use calculated plan dose as an intermediate dose when optimizing a plan. The DVO algorithm calculates the difference between the intermediate dose and the first round optimization result and uses this difference to compensate the optimal result in the consequent iterations. If a new intermediate dose is calculated after the first optimization iteration, the difference is calculated again and it is used to compensate subsequent iterations. Using an intermediate dose is particularly useful if the DVH calculated during optimization deviates from the DVH produced during dose calculation, for example, when there is a lot of heterogeneity in the volume to be treated. Optimization in Eclipse with the DVO was subjected to Optimization convergence errors (OCEs).[11-14] Error is primarily due to the dose calculation for lateral scatter, dose calculation in the build-up region and modeling of transmission. Dose calculation errors are present near electronic disequilibrium region.

Projected DVO describes the intensity of the radiation field. That is at each fluence pixel value indicates how long (In relative terms) a leaf must be open at the position. DVO can produce the large intensity value of one with open field. In DVO, larger value can exist more than the one. The pixel value normalizes so that the optimizer's DVO internal dose calculation has 100% dose at DVO's reference geometry. This means; it's possible that some intensity pixel has value greater than one depending on field setup.

2.3.Progressive resolution optimizer (PRO_ 13.5.35)

PRO is used to optimize MLC aperture of arc field. Progressive multi-resolution strategies are used to get the finer resolution starting with crude approximation.[15] PRO allows Rapid-arc/VMAT fields to avail the Dynamic MLC, variable dose rate and variable gantry speed to produce optimal dose distribution.[16] The PRO algorithm generates a sequence of 178 control points, which define MLC leaf positions and MU/deg as a function of gantry angle. The initial conditions for the PRO algorithm are to defined control points that represent each Rapid-arc/VMAT field. The algorithms are using a multi-resolution approach to optimize the plan. Optimization process goes through four multi-resolution levels, in which number of control points and dose calculation sector increase at each level,

progressively from 10 to 178.[16] This means that; the dose is modeled using first a lower number of dose calculation segments that are distributed evenly in each field. The number of dose calculation segments increases when moving from one multi-resolution level to another. The dose in a dose calculation segment is calculated from the combined fluence through the MLC apertures at the control points located within a certain sector of the arc. Leaf motions are model by interpolating leaf positions between the control points. Leaf tongues are model by modifying the MLC aperture outline to account effectively for the tongue-and-groove effect. The angular resolution of the dose calculation segments gets more accurate as the optimization progresses, and in consequence, the dose gets more meticulous. The number of control points remains the same during the whole optimization.

At the beginning of the optimization, the initial MLC shapes are conform to the targets, and the initial dose rates are equal for all dose calculation segments. The MLC shapes and dose rates of the different control points in the VMAT field are optimizes. During the initial phases of the optimization, bigger adjustments are made in leaf sequencing. The size of these adjustments decreases as the optimization progresses through the levels. During the optimization, the algorithm proceeds through multi-resolution levels progressively increasing the accuracy of the dose calculation. At the first multi-resolution level, only a few dose calculation segments are used to model the dose, and each multi-resolution level contains progressively more dose calculation segments. The angle between the resulting dose calculation segments on the last multi-resolution level- 4 will be approximately 2°- 4°. The total number of dose calculation segments used depends on the span of the arc. Inside each multi-resolution level, there are several steps. Each step has its own internal calculation parameter set. The optimization allows some discontinuities in the delivery during early phases of the optimization, and decreases the size of the discontinuities stepwise as the optimization progresses. The number of steps in different multi-resolution levels varies. Due to the nature of the optimization process, the PRO algorithm is not fully deterministic. Therefore, successive optimizations with the same constraints may yield different results.

Air cavity correction has been incorporated in new PRO optimizer, which applies a finer resolution in the internal dose calculation grid during optimization when air equivalent densities are identified.[9] PRO provides some additional new features including air cavity correction, intermediate dose option and jaw tracking.[14] Air cavity correction is an additional parameter for fine-tuning the inhomogeneities correction by applying finer resolution to calculate the scatter component.

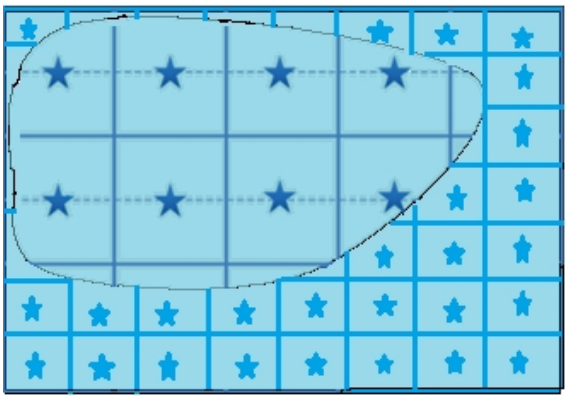

Figure 2: Representation of point cloud structure model in DVO and PRO algorithm.

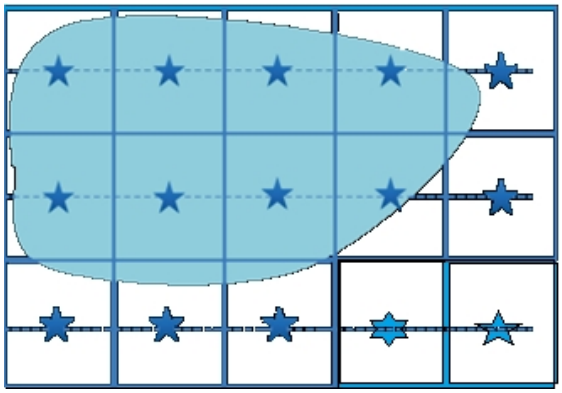

Figure 3: Representation of point cloud structure model in PO algorithm.

2.4. Photon optimizer (PO_13.5.35)

The photon optimization algorithm PO optimizes static field IMRT, Rapid-arc/VMAT and Siemens mARC plan. The PO combines the previous optimization methods used for static field IMRT and arc field IMRT with DVO and PRO respectively. The main difference between the PO algorithm and the earlier optimization algorithms DVO and PRO is that the earlier optimization algorithms used a point cloud model for defining structures. PO algorithm uses a new structural model, where structures, DVH calculation and dose sampling are defined spatially by using one single matrix over the image. The voxel resolution of the matrix is using fixed values of 1.25 mm, 2.5 mm or 5 mm. This resolution defines the planar X and Y resolution in the slices. The Z resolution orthogonal to the slices is a function of choosing resolution and the slice spacing. For example, if the original image has a slice resolution of 1 mm × 1 mm and a slice spacing of 8 mm and the user has defined the optimum resolution to be 2.5 mm, then the optimizer uses the matrix of 2.5 mm × 2.5 mm × 4 mm. This matrix defines the locations of the structures and the sampling of the dose, and it substitutes the previously used point clouds. The DVH for the structure is evaluated using volume weights defined for each voxel.

The volume weight of the voxel defines the ratio of the original structure segment inside the voxel. For small structures, the DVH is super-sampled from the dose matrix to make the DVH look smoother. Figures2 and 3 represents a point cloud structure model for the DVO/PRO and PO respectively, which define the voxels that represents the structure while optimization. These samples also represent the place where the total dose from each field is evaluated.

2.5. Plan quality parameters

2.5.1. Conformity index (CI)

CI is a measure of conformity of isodose encompassing the target. CI was developed as an extension of section-by-section dosimetric analysis and dose volume histogram. RTOG propose the routine evaluation of an external beam treatment plan based on several parameters such as reference isodose value of the treatment plan, reference isodose volume and it can be defined as the ratio of target volume covered by reference volume, to the target volume.[17] CI mathematically defined as,

$$\text{Conformity Index}_{RTOG} = (V_{RI} / TV) \quad (2)$$

where,

V_{RI} = Target Volume covered by reference isodose.
TV = Target Volume.

A CI equal to 1 corresponds to ideal conformation. A CI greater than 1 indicates that the irradiated volume is greater than the targetted volume and it includes healthy tissue. Whereas, if estimated CI value is less than 1 it indicates the target volume is partially irradiated.

2.5.2. Quality index (QI)

RTOG defines QI to investigate the quality of treatment plans. According to RTOG, depending on 90% and 80% of isodose covering the target volume, the quality of irradiation can be estimated. If the 90% isodose covers all clinical and pathological target volumes, treatment is considered to comply with protocol. If 80% of isodose covers all the clinical and pathological target volume, the protocol violation considers as minor. On the other hand, if 80% of isodose not covers the all of the clinical and pathological target volume, the protocol violation considered to be major.[17] QI mathematically defined as,

$$\text{Quality Index}_{RTOG} = (I_{min} / RI) \quad (3)$$

where,

I_{min}= Minimum isodose around the target.
RI = Reference isodose.

2.5.3. Homogeneity index (HI)

HI is defined as the ratio of the maximum isodose to the reference isodose in the target.[17] HI is mathematically defined as,

$$\text{Homogeneity Index}_{RTOG} = (I_{max}/RI) \quad (4)$$

where,

I_{max}= Maximum dose in the target.
RI = Reference isodose.

Ideal HI index considered to be 1. If the homogeneity index is ≤ 2 treatments are considered to be in compliance with the protocol. If this index is between 2 to 2.5 then the protocol violation is considered as minor, but when the index exceeds 2.5 then protocol violation considered to be major, but nevertheless considered to be acceptable.

3. Results

Results consist of averaged parameters were estimated over six distinct study sets and each of the individual study sets are presented. Plan optimized with PO optimizer versus DVO for IMRT and PRO for Rapid-arc were compared, respectively. Evaluated parameters comprise the PTV (maximum, minimum, mean) dose, OAR (maximum, mean) dose, conformity index, quality index, homogeneity index, $PTV_{D95\%Vol}$, $OAR_{D100\%Vol}$, $OAR_{D90\%Vol}$, $OAR_{D80\%Vol}$, $OAR_{D50\%Vol}$, integral plan MU and time taken by the optimizer to optimize the plan. Variation in these plan parameters optimized with PO versus DVO for IMRT were found marginally more than a plan optimized with PO versus PRO for Rapid-arc/VMAT plan. Optimization time was found less with PO compared to other DVO and PRO for both IMRT and Rapid-arc/VMAT plans, respectively.

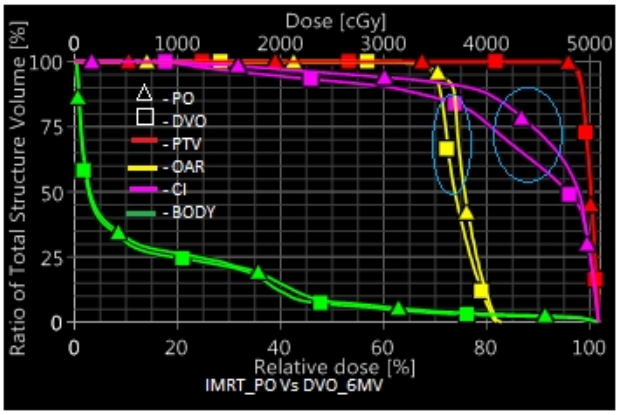

Figure 4: DHV comparison of 6 MV IMRT plan with PO against DVO.

3.1. Comparison of IMRT plan with PO Vs DVO

Table 1 summarizes the comparative result of IMRT plans optimized with PO versus DVO. The average variation in most of the above parameters for plan optimized with PO in comparison with DVO for IMRT created over six phantoms (PSS1-to-PSS6) study sets and 6 MV; 6 MVFFF and 15 MV energies were found minimal. The percentages of the average variation between PO versus DVO optimized plan parameters of PTV maximum, minimum, and mean doses were found 0.23%, 1.67% and 0.09%, respectively, whereas OAR maximum and mean doses were 0.84% and 1.84%, respectively. Similarly, variations in estimated values for

CI, QI, HI, $PTV_{D95\%Vol}$, $OAR_{D100\%Vol}$, $OAR_{D90\%Vol}$, $OAR_{D80\%Vol}$, $OAR_{D50\%Vol}$ and integral plan MU were found 20.4%, 0.77%, 0.52%, 0.63%, 9.57%, 3.54%, 2.46%, 1.95% and 62, respectively.

PTV maximum doses over the all six PSS were found marginally less in the plan optimized with PO than DVO, whereas PTV minimum dose was found more with PO than DVO. This variance found monotonically increasing with energy. Insubstantial variations were observed in a mean dose between the plan optimize with PO and DVO. These variations in OAR side found more than PTV. Similarly, CI and QI values were found more in the plan optimize with PO than DVO. Average variation in CI values over six distinct PSS between PO and DVO were 19.89%, 18.57%, and 22.75% whereas, QI variation were 0.57%, 1.01%, 0.74% for 6 MV, 6 MVFFF and 15 MV energies, respectively. Planned MU was found to be significantly less in the plan optimized with PO than DVO. The average variations over six PSS were 52 MU, 99 MU, and 35 MU for 6MV, 6MVFFF and 15MV, respectively. Optimization time taken by DVO is remarkably more than PO. Percentage of average and maximum optimization time differences found was 9.2% and 21.3%, respectively. Tables 2, 3 and 4 summarize data for each individual plan with OP versus DVO over the six PSS.

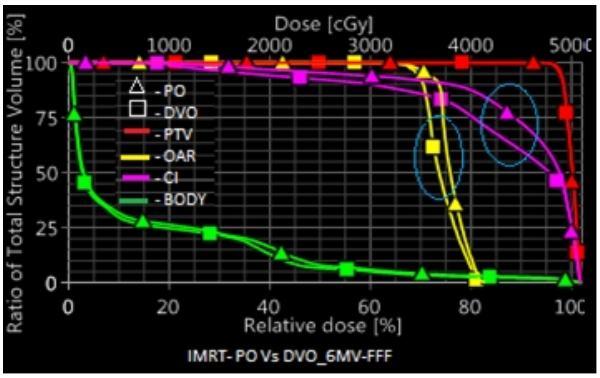

Figure 5: DVH comparison for 6 MVFFF IMRT plan with PO against DVO.

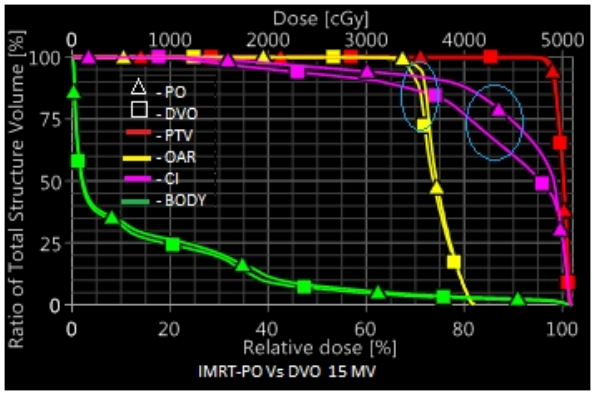

Figure 6: DVH comparison of 15 MV IMRT plan with PO against DVO.

3.2. Comparison of Rapid-arc plan with PO Vs PRO:

Table 5 summarizes the comparative result of Rapid-arc plans optimized with PO versus PRO. The average variation in most of the above parameters for plan optimize with PO in comparison with PRO for Rapid-arc created over six phantoms (PSS1-to-PSS6) study sets as well as 6 MV, 6 MVFFF and 15 MV energies were found to be significant. The percentages of average variation between PO and PRO optimized plan parameters such as PTV maximum, minimum, and mean doses were found 1.18%, 3.38% and 0.19%, respectively. The OAR maximum and mean doses were 1.76% and 2.86%, respectively. Similarly, variations in estimated values for CI, QI, HI, $PTV_{D95\%Vol}$, $OAR_{D100\%Vol}$, $OAR_{D90\%Vol}$, $OAR_{D80\%Vol}$, $OAR_{D50\%Vol}$ and integral plan MU were found to be 8.11%, 2.78%, 1.28%, 2.33%, 9.36%, 5.57%, 4.6%, 4.46% and 20, respectively.

PTV maximum and minimum dose follow same analogy as in IMRT plan. In contrary to IMRT plan, the variance found as monotonically decreasing with energy. Insubstantial variations were observed in mean dose between plans optimize with PO and PRO. However, this variation was found more in Rapid-arc than in IMRT plan. These variations were found to be more for the OAR compared to the PTV. The average variation in CI values over six distinct PSS between PO and PRO were 8.88%, 9.15%, 6.31%, whereas QI variations were 3.3%, 2.79%, and 2.25% for 6 MV, 6 MVFFF and 15 MV energies, respectively. Variation in CI and QI values were less than a factor of two in Rapid-arc plan optimized with PO versus PRO than IMRT plan optimized with PO versus DVO. Remarkable variations were observed in planed MU between plans optimized with PO versus PRO that is in contrary to IMRT plan optimized with PO versus DVO. Planed MU was found to be significantly more in plan optimized with PO than PRO. However, these differences were found more in IMRT plan optimized with the PO versus DVO than Rapid-arc/VMAT optimized with the PO versus PRO. These average variations over six PSS were found to be 22 MU, 22.5 MU and 16 MU for 6MV, 6MVFFF and 15MV, respectively. Optimization time taken by PRO is marginally more than the PO. Percentage of average and maximum optimization time differences found were 1.02% and 4.8%, respectively. Tables 2, 3, and 4 summarize data for each individual plan with OP versus PRO over the six PSS.

Table 1: Average percentage difference for IMRT plan parameters between PO and DVO.

Parameters	6 MV	6 MVFFF	15 MV	%Average
PTV Min Dose (%)	1.18	1.75	2.08	1.67
PTV Max Dose (%)	0.18	0.18	0.33	0.23
PTV Mean Dose (%)	0.08	0.07	0.13	0.09
OAR Max Dose (%)	0.93	0.97	0.63	0.84
OAR Mean Dose (%)	1.73	1.88	0.82	1.48
CI (%)	19.89	18.57	22.75	20.40
QI (%)	0.57	1.01	0.74	0.77
HI (%)	1.15	0.13	0.28	0.52
Plan MU	52.33	99.16	35.00	62.0
*$PTV_{D95\%\ Vol.}$ (%)	0.39	0.49	0.95	0.60
*$OAR_{D100\%Vol.}$ (%)	9.39	9.84	9.55	9.57
*$OAR_{D90\%Vol.}$ (%)	3.83	4.31	2.50	3.54
*$OAR_{D80\%Vol.}$ (%)	2.12	3.72	1.56	2.46
*$OAR_{D50\%Vol.}$ (%)	2.36	2.77	0.73	1.95

Note: *$PTV_{D95\%Vol}$, *$OAR_{D100\%Vol}$,*$OAR_{D90\%Vol}$, *$OAR_{80\%Vol}$, *$OAR_{D50\%Vol}$ mean dose received to 95%,100%, 90%, 80% and 50% volume of PTV and OAR respectively. All the table values are given in % difference between PO and DVO; CI = Conformity Index; QI = Quality Index; HI = Homogeneity Index

Table 2: Estimate parameter of 6 MV energy IMRT and Rapid-Arc plan with PO versus DVO and PRO, respectively, over the distinct phantom study sets (PSS).

Study-Sets	PSS1		PSS2		PSS3		PSS4		PSS5		PSS6	
IMRT-Parameter	PO	DVO	PO	DVO	PO	DVO	PO	DVO	PO	DVO	PO	DVO
PTV Min Dose (%)	92	90.2	92.2	90.4	91.6	89.8	92.1	90.3	91.6	89.6	92.1	90.4
PTV Max Dose (%)	101.9	102	102.5	102.8	101.9	102.1	101.9	102.1	102	102.1	101.9	102.1
PTV Mean Dose (%)	101.6	101.7	101.7	101.6	101.6	101.7	101.6	101.7	106	106	101.7	101.6
OAR Max Dose (%)	83	82	83	82	83	82	83	82	82.8	82.1	83	82
OAR Mean Dose (%)	76	74.4	75.7	74.4	75.9	74.4	76	74.4	74.3	77.2	76.2	74.7
CI	1.31	1.1	1.33	1.1	1.32	1.1	1.32	1.096	1.29	1.084	1.296	1.105
QI	0.996	0.994	0.989	0.978	0.989	0.984	1	0.994	0.989	0.984	0.989	0.984
HI	1.07	1.13	1.074	1.073	1.071	1.073	1.069	1.07	1.068	1.07	1.071	1.07
Plan MU	703	756	695	755	705	757	697	745	650	686	717	780
*$PTV_{D95\%Vol.}$ (%)	98.01	97.66	98.03	97.62	98.07	97.65	98.05	97.66	98.12	97.6	97.9	97.66
*$OAR_{D100\%Vol.}$ (%)	61.95	56.4	61.98	56.86	60.77	56.54	62.34	56.17	57.43	49.4	62.19	57.22
*$OAR_{D90\%Vol.}$ (%)	73.44	70.79	73.03	70.74	73.1	70.79	73.43	70.79	69.47	65.15	75.71	71.09
*$OAR_{D80\%Vol.}$ (%)	74.04	71.66	73.6	71.62	73.88	71.7	74	71.66	71.76	68.75	74.31	72.09
*$OAR_{D50\%Vol.}$ (%)	75.68	73.8	75.33	73.74	75.52	73.84	75.63	73.75	74.13	72.17	75.86	74.17
RapidArc Parameter	PO	PRO	PO	PRO	PO	PRO	PO	PRO	PO	PRO	PO	PRO
PTV Min Dose (%)	90.4	85.6	90.1	87.1	87.3	83.5	85.6	81.4	85.6	82.2	87.5	82
PTV Max Dose (%)	101.9	106.1	104.5	106.5	106.2	108.1	105.9	106.6	107	106.1	105.4	107.4
PTV Mean Dose (%)	100.4	100.4	100.3	100.3	99.2	100.5	100.3	100.5	100.3	100.6	100	100.5
OAR Max Dose (%)	85.7	88.1	86	88.1	87.3	88	86.8	88.6	87.7	88.2	85.9	88.9
OAR Mean Dose (%)	70.7	76.8	71.3	76.6	73.8	75.5	73.5	77	70	73.1	73.3	75.3
CI	1.15	1.15	1.19	1.05	1.1	1.01	1.1	1	1.07	0.99	1.09	1.01
QI	0.984	0.963	0.98	0.95	0.96	0.93	0.94	0.9	0.92	0.9	0.94	0.91
HI	1.09	1.1	1.09	1.1	1.09	1.1	1.19	1.11	1.09	1.1	1.08	1.12
Plan MU	511	491	518	496	508	485	504	491	473	427	536	527
*$PTV_{D95\%Vol.}$ (%)	96.68	95.19	97.36	95.54	96.5	94.7	95.04	93.32	96.34	94.53	96.63	94.32
*$OAR_{D100\%Vol.}$ (%)	42.2	53.53	41.93	51.65	47	43.6	39.34	46.27	36.58	40.1	43.25	42.24
*$OAR_{D90\%Vol.}$ (%)	55.8	65.38	57.04	65.33	62.27	62.4	59.74	66.4	52.6	55.96	59.81	61.14
*$OAR_{D80\%Vol.}$ (%)	62.1	71.04	62.7	70.5	67.1	68.5	67.19	70.64	58.75	62.99	76.14	78.95
*$OAR_{D50\%Vol.}$ (%)	73.3	79.48	73.79	79.15	75.71	78.8	76.18	79.55	73.49	77.45	79.15	81.42

Note: *$PTV_{D95\%Vol}$, *$OAR_{D100\%Vol}$, *$OAR_{90\%Vol}$, *$OAR_{80\%Vol}$ and *$OAR_{50\%Vol}$ mean dose received to 95%, 100%, 90%, 80% and 50% volume of PTV and OAR respectively. % sign indicates table values are given in % dose of prescribe dose of their respective plan; CI = Conformity Index; QI = Quality Index; HI = Homogeneity Index

Table 3: Estimate parameter of 6 MVFFF energy IMRT and Rapid-Arc plan with PO versus DVO and PRO, respectively, over the distinct phantom study sets (PSS).

Study-Sets	PSS1		PSS2		PSS3		PSS4		PSS5		PSS6	
IMRT-Parameter	PO	DVO	PO	DVO	PO	DVO	PO	DVO	PO	DVO	PO	DVO
PTV Min Dose (%)	91.8	90.1	92.1	90.3	91.5	89.7	92	90.2	91.3	89.4	92	90.5
PTV Max Dose (%)	101.9	102.1	102.4	102.8	102	102.1	101.9	102.1	102.1	102.1	102	102.5
PTV Mean Dose (%)	101.5	101.6	101.5	101.5	101.5	101.6	101.5	101.6	101.5	101.6	101.7	101.6
OAR Max Dose (%)	83.1	82	83	82.1	83	82.1	83	82	82.8	82.1	83.1	82
OAR Mean Dose (%)	76.2	74.4	76.1	74.3	76.1	74.3	76.2	74.2	74.4	72	76.4	74.7
CI	1.29	1.09	1.31	1.09	1.3	1.09	1.3	1.09	1.3	1.08	1.29	1.10
QI	0.99	0.98	0.989	0.978	0.989	0.978	1	0.98	0.989	0.984	0.99	0.98
HI	1.07	1.07	1.075	1.074	1.071	1.073	1.071	1.07	1.071	1.07	1.071	1.07
Plan MU	800	881	785	877	803	885	789	864	607	792	828	910
*$PTV_{D95\%Vol.}$ (%)	97.91	97.66	97.93	97	97.98	97.64	97.95	97.66	98.09	97.58	97.82	97.66
*$OAR_{D100\%Vol.}$ (%)	61.9	55.9	61.38	56.41	60.38	55.88	62.04	55.64	56.61	48.14	61.78	56.46
*$OAR_{D90\%Vol.}$ (%)	73.65	70.74	73.48	70.82	73.36	70.63	73.65	70.56	69.31	64.86	74.03	71.05
*$OAR_{D80\%Vol.}$ (%)	74.35	71.67	74.13	71.72	74.2	71.55	74.28	71.45	71.76	68.86	74.6	71.93
*$OAR_{D50\%Vol.}$ (%)	75.95	73.83	75.74	73.85	75.82	73.73	75.89	73.67	74.31	71.93	76.1	74.19
RapidArc Parameter	PO	PRO	PO	PRO	PO	PRO	PO	PRO	PO	PRO	PO	PRO
PTV Min Dose (%)	90.4	85.6	86.2	80.7	86.4	81.2	84	78.7	83.6	84	84.7	81.9
PTV Max Dose (%)	104.8	106.5	107.3	107.8	105.7	107.8	105.6	108.7	106.3	106.9	105.9	106.8
PTV Mean Dose (%)	100.2	100.4	100.4	100.4	100.4	100.6	100.5	100.6	100.4	100.6	100.4	100.5
OAR Max Dose (%)	86.4	89.2	87.6	89.8	87	89.3	86	89.6	87.3	87.9	87.7	89.9
OAR Mean Dose (%)	71	77.3	74.3	76.3	73.2	75.4	73	75.3	72.8	74.4	73.9	75.7
CI	1.16	1	1.08	0.98	1	0.98	1.08	0.97	1.02	0.959	1.06	0.99
QI	0.98	0.94	0.94	0.92	0.94	0.9	0.9	0.88	0.9	0.959	0.91	0.89
HI	1.08	1.1	1.09	1.11	1.09	1.1	1.1	1.12	1.1	1.11	1.1	1.1
Plan MU	569	552	587	528	561	539	559	546	487	481	585	573
*$PTV_{D95\%Vol.}$ (%)	97.21	94.4	96.24	93.2	96.2	93.5	96.02	92.91	95.47	93.1	95.64	93.91
*$OAR_{D100\%Vol.}$ (%)	39.9	48.59	42.61	46.67	43.2	46.2	41.83	39.92	38.76	39.02	43.02	45.23
*$OAR_{D90\%Vol.}$ (%)	55.65	66.18	61.8	63.2	60.43	62.32	58.63	61.23	56.94	59.08	60.23	62.31
*$OAR_{D80\%Vol.}$ (%)	61.7	71.68	68.12	68.7	65.5	67.9	64.32	66.74	63.91	65.43	66.89	68.04
*$OAR_{D50\%Vol.}$ (%)	73.96	79.74	76.97	79.58	75.52	78.39	75.77	78.8	76.42	78.1	76.49	78.88

Note: *$PTV_{D95\%Vol}$, *$OAR_{D100\%Vol}$, *$OAR_{90\%Vol}$, *$OAR_{80\%Vol}$ and *$OAR_{50\%Vol}$ mean dose received to 95%, 100%, 90%, 80% and 50% volume of PTV and OAR respectively. % sign indicates table values are given in % dose of prescribe dose of their respective plan; CI = Conformity Index; QI = Quality Index; HI = Homogeneity Index.

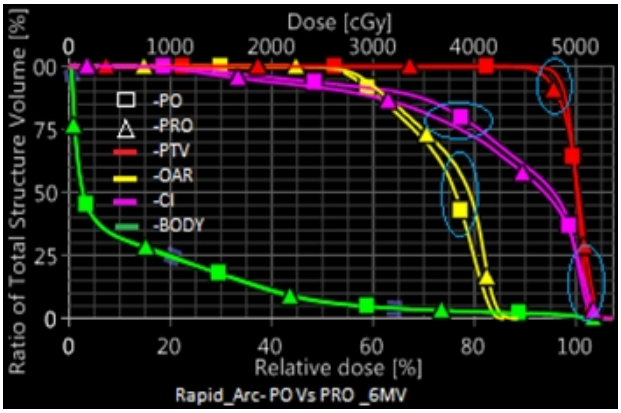

Figure 7: Showing the DVH comparison of 6 MV Rapid-arc plan with PO against PRO.

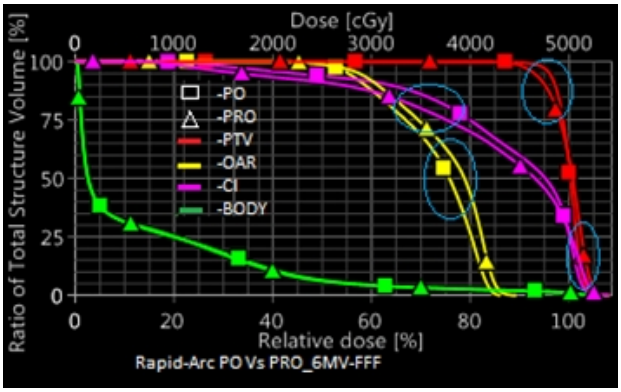

Figure 8: DVH comparison of 6 MVFFF Rapid-arc plan with PO against PRO.

Table 4: Estimate parameter of 15 MV energy IMRT and Rapid-Arc plan with PO versus DVO and PRO, respectively, over the distinct phantom study sets (PSS).

Study-Sets	PSS1		PSS2		PSS3		PSS4		PSS5		PSS6	
IMRT-Parameter	PO	DVO	PO	DVO	PO	DVO	PO	DVO	PO	DVO	PO	DVO
PTV Min Dose (%)	92.2	90.1	92.3	90.1	91.6	89.9	92.3	90.2	92	89.6	92.3	90.3
PTV Max Dose (%)	102	102.1	102.1	102.3	102	102.2	101.9	102.2	102	102.2	102	102.7
PTV Mean Dose (%)	101.8	101.7	101.9	101.7	101.8	101.7	101.6	101.7	101.8	101.7	101.9	101.7
OAR Max Dose (%)	82.6	82.1	82.5	82.1	83.6	82.1	82.6	81.1	82.5	82.2	82.6	82
OAR Mean Dose (%)	75	74.2	74.7	74	74.9	74.2	75	74.2	74	72.7	75	74.4
CI	1.34	1.09	1.35	1.09	1.34	1.09	1.34	1.09	1.3	1.07	1.363	1.10
QI	0.99	0.98	0.98	0.97	0.989	0.978	0.989	0.984	0.989	0.984	0.989	0.984
HI	1.06	1.07	1.071	1.072	1.069	1.072	1.06	1.07	1.06	1.07	1.06	1.07
Plan MU	630	665	624	660	633	667	623	657	602	630	637	977
*$PTV_{D95\%Vol.}$ (%)	98.21	97.56	98.08	97.5	98.21	97.55	98.19	97.56	98.19	97.47	98.2	97.6
*$OAR_{D100\%Vol.}$ (%)	62.6	56.92	62.53	56.87	61.94	56.79	62.82	56.90	60.74	52.84	63.76	57.75
*$OAR_{D90\%Vol.}$ (%)	71.82	70.32	71.38	70.12	71.68	70.21	71.87	70.35	70.46	66.55	71.95	70.92
*$OAR_{D80\%Vol.}$ (%)	72.47	71.47	72.09	71.07	72.38	71.39	72.48	71.50	71.33	69.45	72.59	71.67
*$OAR_{D50\%Vol.}$ (%)	74.35	73.65	74.15	73.38	74.28	73.59	74.35	73.67	73.36	72.31	74.42	73.65
RapidArc Parameter	PO	PRO	PO	PRO	PO	PRO	PO	PRO	PO	PRO	PO	PRO
PTV Min Dose (%)	89.5	85.1	89.7	87.7	85.7	82.8	84.5	82	83.1	83.9	84.3	83
PTV Max Dose (%)	105.1	105.5	104.9	105.8	106.4	106.8	106.1	107.1	105.1	106.9	105.9	106.4
PTV Mean Dose (%)	100.3	100.4	100.3	100.4	100.5	100.5	100.4	100.5	100.4	100.6	100.4	100.5
OAR Max Dose (%)	87	88.5	86	87.4	86.5	88.7	87.2	89.8	86.9	87.9	86.4	88.3
OAR Mean Dose (%)	73.2	73.7	72.6	74.8	75.5	76	72.8	74.8	71.7	72.5	74.9	75.2
CI	1.11	1.04	1.13	1.04	1	0.96	1.07	0.97	1.03	0.965	1.08	1
QI	0.957	0.95	0.97	0.95	0.92	0.90	0.93	0.88	0.915	0.90	0.905	0.89
HI	1.092	1.097	1.09	1.1	1.09	1.1	1.09	1.11	1.1	1.11	1.08	1.1
Plan MU	407	386	416	395	394	372	414	383	379	353	425	420
*$PTV_{D95\%Vol.}$ (%)	96.46	95.04	96.8	95.67	95.46	93.21	96.17	93.83	95.39	93.9	97.78	94.44
*$OAR_{D100\%Vol.}$ (%)	48.8	47.20	48.16	45.88	46.52	43.05	41.55	48.13	44.04	44.66	47.20	47.46
*$OAR_{D90\%Vol.}$ (%)	61.10	60.46	58.94	61.55	64.51	63.83	59.39	60.24	56.63	55.39	63.09	61.72
*$OAR_{D80\%Vol.}$ (%)	66.4	65.63	66.16	66.71	69.32	68.61	64.69	66.30	62.55	61.57	68.24	67.12
*$OAR_{D50\%Vol.}$ (%)	74.9	67.44	75.19	77.78	77.54	78.62	75	78.04	74.27	76.28	77.20	78.33

Note: *$PTV_{D95\%Vol}$, *$OAR_{D100\%Vol}$, *$OAR_{90\%Vol}$, *$OAR_{80\%Vol}$ and *$OAR_{50\%Vol}$ mean dose received to 95%, 100%, 90%, 80% and 50% volume of PTV and OAR respectively. % sign indicates table values are given in % dose of prescribe dose of their respective plan; CI = Conformity Index; QI = Quality Index; HI = Homogeneity Index

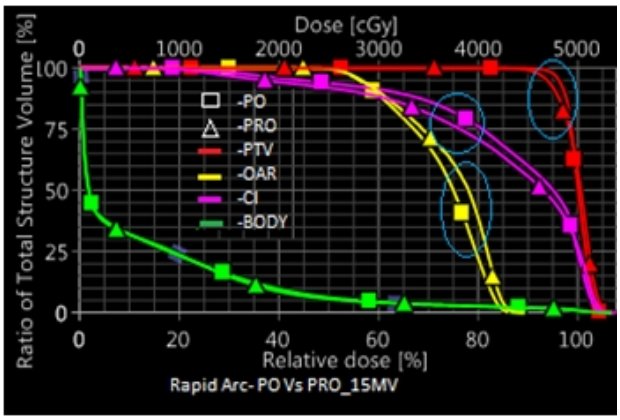

Figure 9: DVH comparison of 15 MV Rapid-arc plan with PO against PRO.

Table 5: Average percentage difference for Rapid-Arc Plan parameters between PO and PRO.

Parameters	6MV	6MVFFF	15MV	% Average
PTV Min Dose (%)	4.11	3.97	2.06	3.38
PTV Max Dose (%)	1.45	1.45	0.66	1.18
PTV Mean Dose (%)	0.33	0.13	0.1	0.19
OAR Max Dose (%)	1.75	2.2	1.33	1.76
OAR Mean Dose (%)	3.62	2.7	2.14	2.82
CI (%)	8.88	9.15	6.31	8.11
QI (%)	3.3	2.79	2.25	2.78
HI (%)	1.37	1.57	0.9	1.28
Plan MU	22.16	21.5	16.02	20
*$PTV_{D95\%\,Vol.}$ (%)	1.88	2.76	2.06	2.33
*$OAR_{D100\%Vol.}$ (%)	14.51	8.06	5.52	9.36
*$OAR_{D90\%Vol.}$ (%)	8.67	5.99	2.05	5.57
*$OAR_{D80\%Vol.}$ (%)	7.03	4.77	2.02	4.6
*$OAR_{D50\%Vol.}$ (%)	5.54	4.05	3.81	4.46

Note: *$PTV_{D95\%Vol}$, *$OAR_{D100\%Vol}$,*$OAR_{D90\%Vol}$, *$OAR_{80\%Vol}$,*$OAR_{D50\%Vol\ mean}$ dose received to 95%, 100%, 90%, 80% and 50% volume of PTV and OAR respectively. All the table values are given in % difference between PO and PRO; CI = Conformity Index; QI = Quality Index; HI = Homogeneity Index

4. Discussion

The purpose of this study was to present the efficiency and accuracy of different optimizers used for IMRT and Rapid-arc/VMAT technique in Eclipse TPS. From the result of several IMRT and Rapid-arc/VMAT plans over distinct energy and a distinct PSS, the behavior of PO versus DVO and PRO can be explained quantitatively and qualitatively. Quantitative analysis of newly incorporated optimizer PO against DVO and PRO for IMRT and Rapid-arc/VMAT respectively, is shown in Tables 2, 3, and 4. PO is based upon same principle as DVO and PRO. PO still uses a MRDC dose calculation algorithm during optimization to speed up dose calculation. Nevertheless, changes were observed between PO versus DVO and PRO. This can be predominantly explained with the help of fundamental change made in PO optimizer. In DVO and PRO, every structure is represented by its own point cloud and dose is calculated for every dose point of each structure, whereas, in PO whole patient is replaced by a point cloud with single fixed 3D grid size. This grid size decides the size of the voxel as well as a number of voxel within each contour for DVO and PRO plan optimization. Point cloud principle provides more degrees of freedom for the DVO and PRO optimizer whereas, less in the PO. Optimization algorithm and dose calculation engine calculate dose for each of voxel in contour. It is very important to understand the concept of dose point. The number of dose point, i.e., number voxel generated inside contour with DVO, PRO, and PO optimizer based on the principle of point clouding with same grid spacing are different. Accuracy of calculated maximum, minimum, and mean doses are function of the number of dose point inside the contour. Higher the number of dose points, more accurate is dose calculation. Consequently, variation in values of these parameters were observed due to the number of dose points in contour. Grid size automatically defines for DVO and PRO optimizer at time of optimization in optimization window depending on the volume of contour, e.g., larger volume structures like body, bowel, and bladder define high grid size. Whereas, smaller volume structures like optic nerve, chiasm, and cochlea define smaller grid size. Additionally, user can define grid size manually in the optimization window. These optimizers define increased number of dose points (i.e. number of voxel) at the periphery of contour than at the center. However, in case of PO, only one grid size can be defined manually, and no liberty has been provided at the user end individually as per structure. Major differences were found in maximum, minimum, and mean dose for PTV and OAR due to the dose calculation strategies of optimizer dealing with point cloud distinctly in PO, DVO, and PRO. Also, one of major influential factors is that DVO does not taken into account for air cavity correction whereas, PO and PRO both take into accounts for air cavity correction during plan optimization. This causes variation in plan quality parameter differently in PO versus DVO and PRO. DVO is subjected to optimization conversance error (OCEs).[12-15] All of the DVO, PRO, and PO fast optimizer cause OCEs, and errors are basically due to dose calculation in buildup region, dose calculation for lateral scatter and modeling of transmission.[9] It has been observed that OCEs behaviors are different for each of DVO, PRO, and PO. Intermediate dose calculation option is introduced in recent version in order to improve OCEs. However, quantification and nullification of this error are still difficult. DVO optimizer was found more inconsistent and shows the former behavior compared to PO and PRO. This yields variation in the estimated parameters, and variations were found more in IMRT plan optimized between PO versus DVO than the Rapid-arc/VMAT plan optimized with PO versus PRO.

Qualitative investigation of DVO, PRO, and PO optimizer was performed based on estimated parameters such as CI, QI, HI, total plan MU, and time taken by optimizer to optimize the plan. Calculated values of CI indicate that

conformity in planned optimized with DVO and PRO is marginally better than the planned optimized with the PO. This indicates that DVO and PRO produced more conformal plan comparative to PO. In contrary, values of QI stipulate PO produced a better quality of treatment plan comparative to DVO and PRO, i.e. PO produced plan with better coverage to the target volume. This leads to the spillage of small-scale prescription dose around the PTV in the plan optimized with PO than DVO and PRO. Insignificant differences were found in values of HI between PO versus DVO and PRO for IMRT and Rapid-arc/VMAT plans, respectively. All these three optimizers taken into account for the inhomogeneity correction; however each optimizer deals with inhomogeneity correction very distinctly, thus leading to variation in integral planned MU in plan optimized with PO versus DVO and PRO for both IMRT and Rapid-arc/VMAT plans, respectively. PO generates lesser segment for static segmented IMRT as well as smart dynamic sliding window for Rapid-arc/VMAT compared to DVO and PRO, respectively. PO produced a better quality IMRT plan with less number of MU than DVO, whereas in Rapid-arc/VMAT PO produced the plan with slightly higher number of MU than PRO. Similarly, PO takes less time to optimize the plan than DVO and PRO.

Quality of the plan can be estimated from the DVH, which provides graphical representation of volume versus dose. Figures 4, 5, and 6 show the DVH comparison between two different IMRT plans optimized with PO versus DVO for 6 MV, 6 MVFFF and 15 MV, respectively. These figures were selected based on average variation found over the distinct PSS and energy for IMRT and Rapid-arc/VMAT. The DHV shown in these figures indicate a major variation of dose received by volume between two different plans optimized with PO and DVO. Similarly, Figures 7, 8, and 9 show the DVH comparison between two different Rapid-arc/VMAT plans optimized with PO versus PRO for 6 MV, 6 MVFFF and 15 MV, respectively. Figures 4, 5, and 6 for IMRT plan show that the variation in the DVH over the PTV were found negligible. Both the DVH of plan optimized with the PO and DVO are almost overlapping. However, meaningful deviation were found towards the OAR side. In Figures 7, 8 and 9 for Rapid-arc/VMAT plan, it was observed that the DVH over both of the PTV and OARs showing meaningful deviation between plans optimized with PO and PRO. The limitation of the proposed study is that the study was carried out with virtual phantom rather than on real patient CT images. Evaluation of the actual clinical impact of optimizer can be further investigated by performing treatment planning on the CT images of real cancer patients.

5. Conclusion

This study was conducted for an evaluation of newly incorporated optimizer PO against DVO and PRO for IMRT and Rapid-arc/VMAT plans, respectively. Selection of the optimization algorithm during IMRT and Rapid-arc/VMAT plan determines plan efficiency, accuracy, and optimal final dose distribution. The CI, QI, HI, integral planned MU, optimized time, and other dosimetric results obtained using optimizer PO was found to be more consistent and accurate than using DVO and PRO. The results presented in this study showed that PO generates plans with better quality in shorter time compared to DVO and PRO for both IMRT and Rapid-arc/VMAT, respectively.

Conflict of interest

The authors declare that they have no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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